# Maximum Brightness and Post-Maximum Decline of Light Curves of SN Ia: A Comparison of Theory and Observations

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## ABSTRACT

We compare the observed correlations between the maximum brightness, postmaximum decline rate and color at maximum light of Type Ia supernovae (SN Ia) with model predictions.

The observations are based on a total of 40 SN Ia with 29 SN of the Calan Tololo Supernova Search and 11 local SN which cover a range of $\approx 2^m$ in the absolute visual brightness. The observed correlations are not tight, one dimensional relations. Supernovae with the same postmaximum decline or the same color have a spread in visual magnitude of $\approx 0.7^m$. The dispersion in the color-magnitude relation may result from uncertainties in the distance determinations or the interstellar reddening within the host galaxy. The dispersion in the decline rate-magnitude relation suggests that an intrinsic

spread in the supernova properties exists that cannot be accounted for by any single relation between visual brightness and postmaximum decline.

Theoretical correlations are derived from a grid of models which encompasses delayed detonations, pulsating delayed detonations, the merging scenario and helium detonations. We find that the observed correlations can be understood in terms of explosions of Chandrasekhar mass white dwarfs. Our models show an intrinsic spread in the relations of about $0.5^m$ in the maximum brightness and $\approx 0.1^m$ in the B-V color. Our study provides strong evidence against the mechanism of helium detonation for subluminous, red SN Ia.

## 1. INTRODUCTION

Supernovae of Type Ia are the most luminous stellar objects and, in principle, can be used to determine extragalactic distances and the cosmological parameters. Their use as standard candles is based on the assumption that they form a homogeneous group. Type Ia Supernovae (SN Ia) were, however, long suspected not to be perfectly homogeneous both from the light curves and the spectra (Pskovskii 1970, 1977, Barbon, Ciatti & Rosino 1973, 1990, Branch 1981, Elias et al. 1985, Frogel et al. 1987, Phillips et al. 1987, Cristiani et al. 1992). The discovery of the strongly subluminous supernova SN 1991bg established the existence of a wide range of luminosities among SN Ia (Filippenko et al. 1992, Leibundgut et al. 1993). New, uniform data sets of high quality confirm this diversity (Hamuy et al. 1993, Maza et al. 1994, Suntzeff, 1995, Hamuy et al. 1996). From these data, the existence of a correlation between the maximum brightness and the shape of the light curves was established and used to correct for the variations in the absolute brightness and to determine $H_o$ (Phillips 1993, Hamuy et al. 1995, Riess, Kirshner & Press 1995).

It is widely accepted that SN Ia are thermonuclear explosions of carbon-oxygen white dwarfs (Hoyle & Fowler 1960). The three main scenarios are the explosion 1) of a Chandrasekhar mass white dwarf, (Arnett 1969, Nomoto et al. 1976, 1984 , Khokhlov 1991), 2) of merging white dwarfs (Tutukov & Yungelson 1983, Iben & Tutukov 1984, Webbink 1984), and 3) of a low mass white dwarf triggered by a helium detonation at its surface as suggested by Nomoto et al. (1980) and Woosley, Taam & Weaver (1980). Within each scenario different amount, of $^{56}Ni$ can be produced depending on details of the progenitor evolution, presupernovae structure and flame propagation. Because Ni is the main energy source for the light curve, the brightness of the models must be expected to vary. Detailed modeling of the LCs shows that they differ both in their brightness and shape, but their physical correlation differs depending on the scenario (Höflich, Khokhlov & Müller 1993). Therefore, a comparison between theory and observations can be used to discriminate explosion scenarios. The theoretical relation can be further used to determine $H_o$ independent from secondary distance indicators needed in purely empirical determination (Müller & Höflich 1994, Höflich & Khokhlov 1996, and references therein).

In this letter, we compare the observed correlations between maximum brightness, the post-maximum decline and colors of the visual light curves of SN Ia with theory. The post-maximum decline is characterized by the parameter $\Delta M_V(t)$ defined as the difference between the brightness at maximum light and that $t$ days later. The comparison is based on 40 well observed supernoave and our light curve calculations of a set of 42 models. The list of supernovae includes the uniform set 29 supernovae obtained with the Calan Tololo Supernova Search (SN1990O, 90T, 90Y, 90af, 91S, 91U, 91ag, 92J, 92K, 92P, 92ae, 92ag, 92al, 92aq, 92au, 92bc, 92bg, 92bh, 92bl, 92bo, 92bp, 92br, 92bs, 93B, 93H, 93O, 93ag, 93ah) and 11 nearby supernovae (SN1937C, 72E, 80N, 81B, 86G, 89B, 90N, 91T, 91bg, 92A, 94D) (see Hamuy et al. 1996).

## 2. OBSERVATIONS VS. THEORY

To illustrate the nature of $\Delta M_V(t)$, we show in figure 1 four theoretical V light curves based on different explosion scenarios. The function $\Delta M_V(t)$ provides a particular measure of post-maximum decline rate. The color (V) in which the comparison is made, and the value of the time base t must be chosen carefully. We use the visual wavelength range because, past maximum light, most of the energy is emitted in V and, consequently, the theoretical LCs are most accurate in V. Moreover, the spectral variation of the flux across the V filter is smaller than in other bands, e.g. B or R. Consequently, differences induced by the assumed transmission of filters and those actually used during the observations will be smallest (Höflich 1995). We have found that a time base of 15 days, previously used in B by Phillips (1993), does not permit a clear distinction between different visual LCs, because the decline rate in V is much smaller than in B. Moreover, a value of $\Delta M_V(15)$ is not that sensitive to the postmaximum decline, but is strongly influenced by the broadness of the maximum. On the other hand, a very long base will measure predominantly the exponential decay at late times. We find that t=20 days is a better choice in order to differentiate the various light curves in V.

In figure 2, the observed absolute visual brightness $M_V$ is plotted as a function of $\Delta M_V(20)$ based on the LCs observed at CTIO (Hamuy et al. 1996). The errors are estimated as follows: In $M_V$, uncertainties are due to uncertainty in the apparent magnitude. For those SN which were observed at maximum, we

estimate an uncertainty of 0.05 mag. For those not observed at maximum light, $M_V$ is determined by fitting template curves to *extrapolate* to a peak magnitude.

In so doing we are essentially comparing the brightnesses at maximum light given by the various templates employed. This technique provides a way to estimate our uncertainty in guessing a quantity that was not observed. For instance, if the best fit yields $V_{max} = 15.00^m$ and the next-best-fit yields 15.25, we quote $V_{max} = 15.00 \pm 0.25$. Therefore, our error estimates for the peak luminosities are larger than 1 $\sigma$ since they cover a range of confidence larger than 67%. Given this uncertainty in the peak apparent magnitude, we add in quadrature an estimate of the foreground extinction correction (0.045 mag), an estimate in the K-term correction (0.02 mag), and the uncertainty of 600 km s$^{-1}$ in the velocity of the cosmological expansion due to the correction for peculiar motions. Another source of error, not included in the error bars (see below), is due to the distance determination of the host galaxies which are based on Tully-Fisher (1977) and surface bightness fluctuation (Tonry & Schneider 1988). For $\Delta M_V(20)$, we adopt an error of $0.05^m$ for those SN whose light curves were observed from maximum light through day 20 and $0.10^m$ for others.

The correlation between $M_V$ and $\Delta M_V(20)$ can be clearly seen in Fig. 2. With decreasing brightness at maximum light, supernovae decline faster. There is, however, a spread in $M_V$ of about $0.7^m$ within the relation. This spread is larger than the estimated error. It may be explained either by the error in the individual distance determinations, reddening in the host galaxy, or by an intrinsic spread among SN Ia with the same $\Delta M_V(20)$, or by a combination of all these effects. In the first case, this would imply an uncertainty of $\approx$ 40 % in the distance determinations. This is much larger than the relative uncertainties of the Tully-Fisher and the surface brightness fluctuation which are 12 % and 10 %, respectively (Jacoby et al. 1992). The error in $E_{B-V}$ of the host galaxy of less than $0.1^m$ is probably realistic. Taking the latter error estimates, we are forced to assume an intrinsic spread of $M_V$ of $\approx 0.3 - -0.6^m$ of SN Ia at a given $\Delta M_V(20)$.

The theoretical relation between $M_V$ and $\Delta M_V(20)$ is shown on the right panel of Fig. 2. The models do provide a spread in $M_V$ within each explosion scenario, and $\Delta M_V(20)$ decreases with $M_V$. The largest

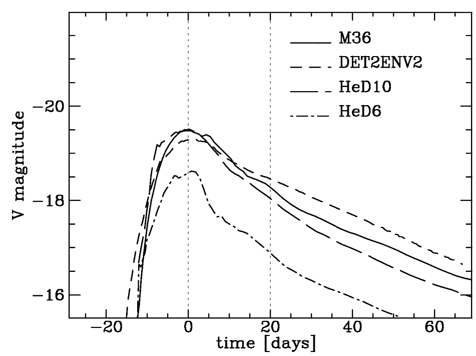


Fig. 1.— Visual light curves for the delayed detonation model M36, the envelope models DET2ENV2, and the helium detonations HeD6 and 10 (from Khokhlov et al. 1993, Höflich 1995, Höflich & Khokhlov 1996). The two vertical lines mark the time of maximum light and 20 days later. Note, that for HeD6, $\Delta M_V(20)$ does not provide a good measurement for the post-maximum decline.

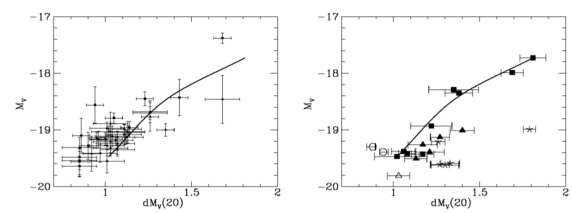


Fig. 2.— Observed $M_V$ as a function $\Delta M_V(20)$ (left plot) normalized to $H_o = 65 km/(Mpc\ s)$ (Hamuy et al. 1995, Höflich & Khokhlov 1995). In the right plot, the theoretical models are shown for the delayed detonation (open triangle: N-series, Khokhlov 1991; black triangles: M-series, Höflich 1995), pulsating delayed detonations (black circles) and merging scenarios (open circles) (Khokhlov, Müller & Höflich 1993, Höflich, Khokhlov & Wheeler 1995, Höflich & Khokhlov 1995) and the helium detonations (asteriks, Höflich & Khokhlov 1996). The correlation between $M_V$ and $\Delta M_V(20)$ within each set of models is evident. Note that the models of the M- and N-series do produce different relations. Although both are based on the delayed detonation mechanism, the flame velocities and pre-supernova structures are different. The curve represents the theoretical relations for pulsating delayed detonations given in both plots for orientation.

variation is among delayed and pulsating delayed detonations. Both scenarios show qualitative agreement with the observations within the error bars. For normal bright delayed detonations, however, the postmaximum decline is somewhat steeper than observed. If this systematic tendency is real, models with a lower central density of the exploding white dwarfs may be preferred or expanding envelopes with a more pronounced shell-like structure may be favored. helium detonations fall well outside the observed range. They decline much too fast.

In Figure 3, we give B-V as function of $M_V$ for observed supernovae and our models. With decreasing maximum brightness supernovae become redder (Fig. 3). The color relation again shows a substantial scatter. The reasons may be interstellar reddening (Miller & Branch 1994), errors in the distance determination (see above), errors intrinsic to the observations, and/or may reflect an intrinsic spread of properties of Type Ia supernovae. Qualitatively, models for the explosion of Chandrasekhar mass white dwarfs follow, within the uncertainties, the same $(B-V)-(M_V)$ relation as the observations. For these models, the intrinsic spread of the B-V relation is apparently of the order of $0.1^m$. Given the intrinsic uncertainties and approximations used for the light curve calculations, the discrepancies are well within the expected errors. NLTE-effects, for instance, tend to produce slightly bluer colors ($\approx 0.02--0.05^m$) at maximum light compared to our light curve-colors (Höflich 1995). Another possible source of systematic errors entering the comparison is connected to the filter response functions of the observations and those used for the theoretical light curves. For dim supernovae, the models are slightly bluer. This can be explained by interstellar reddening, but is more likely due to selective line blanketing (Branch, private communication) or dust formation (Dominick et al. 1995, Höflich & Khokhlov 1996).

helium detonations show a rather blue color even if somewhat subluminous. Their color is clearly in agreement with bright SN Ia. A very large reddening would be required in order to reproduce the observed extremely subluminous SN Ia. For SN1992K, for instance, $E_{B-V}$ must be as large as $0.7^m$ (Hamuy et al. 1994). This would mean an intrinsic brightness of $-20.7^m$ assuming $A_V = 3.1\ E_{B-V}$ which is inconsistent with the helium models and is out of the reach of even pure detonation models of Chandrasekhar mass white dwarfs ($M_V = -20^m$, Khokhlov et al. 1993).

## 3. CONCLUSIONS AND DISCUSSION

The observed correlations between the absolute brightness and the postmaximum decline rates and B-V color can be understood in terms of explosions of Chandrasekhar mass white dwarfs. In these models, the variation in brightness is due to different amounts of $^{56}Ni$ produced in the central region. If little Ni is produced, the envelope stays cooler. This has two effects: the color is redder and the photosphere recedes faster at maximum light which results in a fast postmaximum decline (Höflich & Khokhlov 1996 and references therein).

For the very same reason, helium detonations show different behavior. In those models, a significant amount of Ni is present in the outer layers. This heats up the photosphere and keeps it hot even in subluminous explosions. The color remains blue. This implies that the red color observed in subluminous SN Ia must be attributed to interstellar reddening. This, in turn, is incompatible with the maximum brightness (see above). In addition, the postmaximum decline of helium detonations is always steep because, near maximum light, the outer region with substantial $^{56}$Ni becomes transparent to $\gamma$ rays. This results in a rapid increase of the escape probability and, consequently, in a rapidly declining light curve even for bright SN Ia. Note that, for normal bright supernovae, early time spectra indicate expansion velocities of Si-rich layers in excess of 19,000 km/sec (e.g. 1990N, Leibundgut et al. 1991; SN1994D, Höflich 1995, SN1995E, Riess, private communication). In contrast, both 1-D and 2-D model calculations for helium detonations predict velocities smaller than 14,000 km/sec for these layers (Woosley & Weaver 1994, Livne & Arnett 1995,

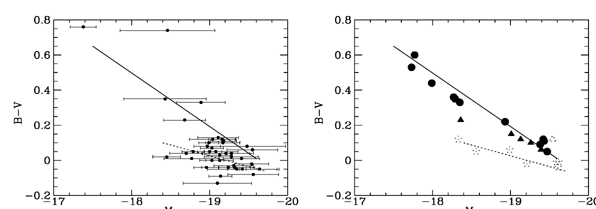


Fig. 3.— Observed (left, normalized to $H_o = 65 km/(Mpc\, s)$) and theoretical (right) plot of B-V as a function of $M_V$ for the same supernovae and models as in Fig. 2. The observational errors in the B-V are of the order of a few hundreds of a magnitude. The line show the approximate relation for delayed detonations (solid) of the M-series and helium detonations (dashed).

Höflich & Khokhlov 1996). The restriction of Si to low velocities must be regarded as a generic feature of helium detonations. Within this scenario, a minimum of 0.15 to 0.2 $M_\odot$ of He atop the carbon-oxygen WD is required. Explosive burning of helium at low densities produces mainly $^{56}$Ni. To make helium detonations consistent with the limits from early spectra both with respect to the appearance of strong Si lines and the absence of strong Ni lines, the burning products of the outer, former He shell ( $M_{He} \approx 0.1$ ... $0.2 M_\odot$) must accelerated to velocities well above $\approx 16000...18000 km/sec$. The energy required would be well in excess of the total energy of a thermonuclear explosion. For more details, see Höflich & Khokhlov (1996).

Models do not give one-parameter relations for $M_V - \Delta M_V(20)$ and $(B-V) - M_V$. If a single monotonic relation is used (see Figs. 2 & 3), then a spread exists around this relation of $0.5^m$ in $M_V$ and $0.1^m$ in B-V. Thus, even within a given explosion scenario, models with different flame velocities and pre-supernovae structures do produce the same $M_V$ but produce different colors and light curve shapes as a comparison of the models of the N- and M- series reveals (Figs. 2 & 3).

The observations show an even larger spread in both the $M_V - \Delta M_V(20)$ and $(B-V) - M_V$ relation. This may be partially attributed to uncertainties in the distances and interstellar reddening. Within these uncertainties, the observed $(B-V) - M_V$ relation may be consistent with a one-parameter relation because the reddening correction enters both B-V and $M_V$. For the $\Delta M_V(20) - M_V$ relation, however, the reddening correction enters $M_V$ only. To attribute the observed spread in $\Delta M_V(20) - M_V$ to the reddening alone would require a mean $E_{B-V}$ of at least $0.2^m$. Based on the statistical studies of Miller & Branch (1994) and our individual fits of SN Ia light curves, we regard the implied mean reddening as rather unlikely. This unacceptably high value indicates that at least a part of the variation is intrinsic to SN Ia. To distangle the different causes of the spread, detailed analyses of the entire light curves and spectra and deeper understanding of the physics of the stellar evolution and explosion is required.

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